NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Maryland 20034

A STRUCTURE-FLUID INTERACTION CAPABILITY FOR THE NASA STRUCTURAL ANALYSIS (NASTRAN) COMPUTER PROGRAM

Francis M. Henderson

COMPUTATION AND MATHEMATICS DEPARTMENT

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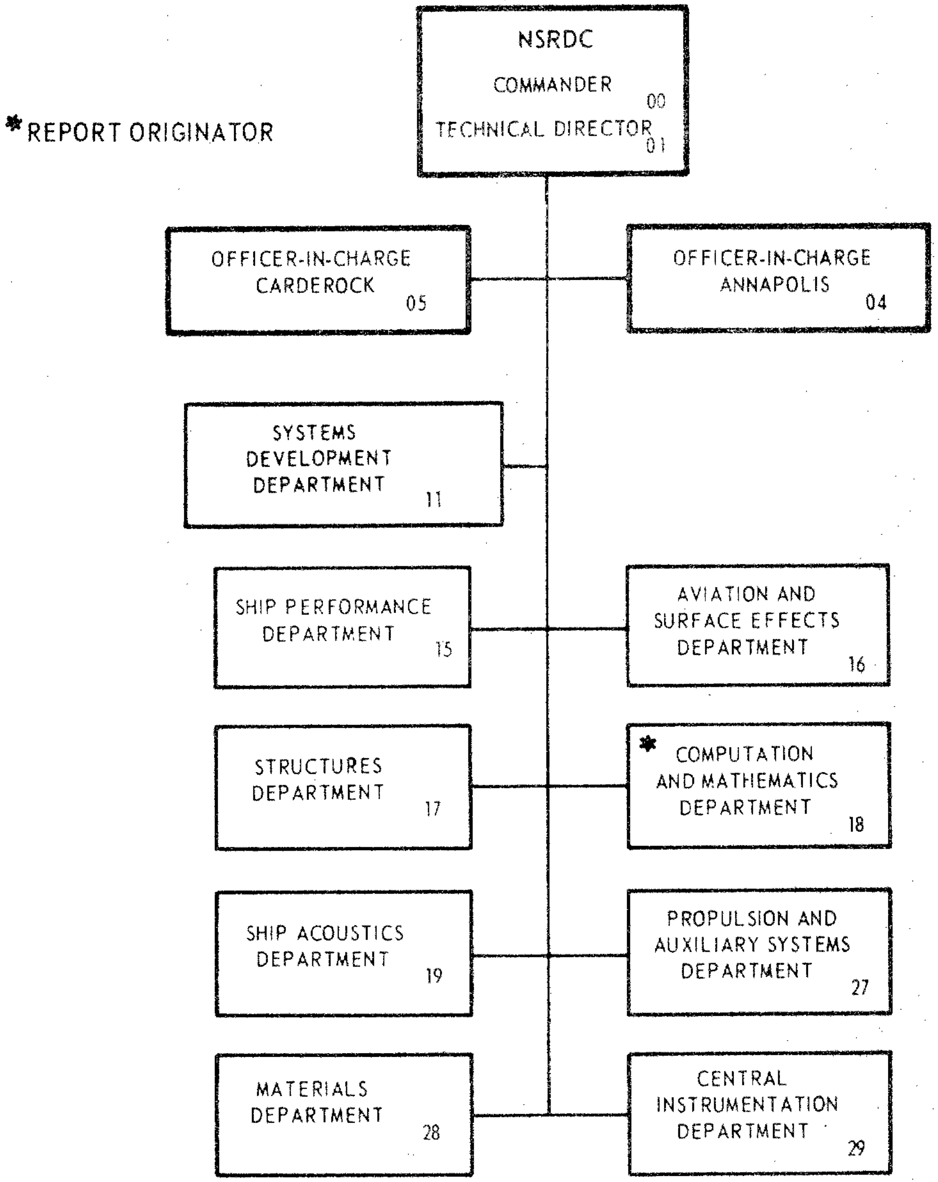

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A STRUCTURE-FLUID INTERACTION CAPABILITY FOR THE NASA STRUCTURAL ANALYSIS (NASTRAN) COMPUTER PROGRAM

by

Francis M. Henderson

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NOTATION

a	Radius of sphere
A	Area of acoustic surface element
c	Speed of sound in water
F	Magnitude of harmonic exciting force
k	Wave number of sound pressure wave, $= \omega/c$
p	Sound pressure (complex-valued)
q	Normal gradient of pressure
q_{ji}	Element of the surface normal mobility matrix
S	A closed surface
u	In-vacuo normal surface velocity
v	In-fluid normal surface velocity
v_0	An arbitrary reference velocity
w	Component of fluid particle velocity normal to the structural surface S
$\underline{y}$, $\underline{y}'$	Structural surface points
$Z_{n\ell}$	Loaded mechanical impedance of a shell
ζ_n	Acoustic impedance ratios
ρ	Mass density of fluid medium
ω	Angular frequency of vibration

ABSTRACT

This report describes a method for incorporating the structure-fluid interaction effect into NASTRAN dynamic frequency response calculations for submerged structures. The interaction equation is derived by incorporating the effect of dynamic surface mobility into the equations which approximate the surface Helmholtz integral equation and by requiring velocity compatibility at the fluid-surface interface. The method is implemented through an interface between the computer program, XWAVE, for acoustic pressure calculations and NASTRAN. The method is demonstrated by calculating the shell surface-fluid interaction pressures on a hollow sphere submerged in an infinite fluid and excited by a radial point harmonic forcing function. The surface pressure results are compared with values calculated using an analytic formula of M. C. Junger.

ADMINISTRATIVE INFORMATION

The work reported here was conducted partially under Task Area SF 14532106, Task 15326, and partially under Task Area ZR 0140201, Task 13300.

I. INTRODUCTION

An approach for including the shell-fluid surface interaction effect into the dynamic analysis of submerged vibrating structures has been investigated.* The method, essentially that described by Chen[1], utilizes the in vacuo dynamic mobility characteristics of the shell surface and compatibility of velocities and forces at the shell-fluid boundary to obtain a system of coupled equations of motion for structure and fluid.

At the time of the original investigation, several methods for effectively calculating the elements of the in vacuo dynamic mobility matrix were being explored. One method, in particular, involved the calculation of these elements directly through use of NASTRAN's rigid formats, 8 and 11, for dynamic frequency response.

This report reviews briefly some general features and capabilities of the acoustic program, XWAVE, and the modification of the surface pressure equation to include structure-fluid interaction and demonstrates by a calculation the XWAVE-NASTRAN interface.

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* Informally documented in Technical Note CMD-24-71, "Computation of the Sound Pressure Field About Submerged Vibrating Structures by a Method of G. Chertock," by F. Henderson, August 1971.

1 Chen, L., and D. Schweikert, "Sound Radiation from an Arbitrary Body," The Journal of The Acoustical Society of America, Vol. 35, No. 10 (October 1963).

II. XWAVE

XWAVE is a digital computer program which numerically solves the Helmholtz integral equations for the sound pressure on the surface of the vibrating structure and in the exterior fluid medium (near- and far-field), when the surface geometry, normal surface velocity, and wave number are specified. The unique feature of XWAVE, distinguishing it from the community of such computer programs, is its capability for very rapidly evaluating coefficients of the approximating matrix equations. These equations are obtained by discretizing the structural surface into a network of small connected patches whose areas are assumed small enough that integrands may be taken as essentially constant over them. The rapid coefficient evaluation is due to techniques devised by Dr. George Chertock[2] of the Ship Acoustics Department. The solution of the matrix system for surface pressure is obtained by a standard Gauss-Seidel iteration method.

XWAVE is written entirely in FORTRAN and runs on the CDC 6700 computer at the Center's Computation and Mathematics Department.

Although the application of XWAVE is best suited to structures with arbitrary surface geometries, special options have been included for handling surfaces of revolution where symmetry planes arise from symmetries and/or anti-symmetries in the normal velocity boundary conditions. In these cases only the nonredundant parts of the surface geometry and velocity distribution are input to the program, the remainder being calculated internally by XWAVE via reflection in the symmetry planes. This procedure permits a significant increase in

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[2] Chertock, G., "Integral Equation Methods in Sound Radiation and Scattering From Arbitrary Surfaces," NSRDC Report 3538 (June 1971).

the number of "effective" acoustic surface elements (or areas) that can be described using a given order of matrix equation. Table 1 compares CDC 6700 computer times obtained using XWAVE in applications with and without symmetries.

For surfaces of revolution, XWAVE provides special subroutines which will generate automatically most of the surface geometric quantities (coordinates of element centroids, element areas, unit normal coordinates, curvatures, etc.) required in setting up the matrix equations. The present version of the data generator can produce such shapes as disks, annular rings, cones, and cylinders either individually or pieced together as shown in Figure 1. This capability has found application recently in the acoustic element modeling of cylinders with flanges.

The options for treating symmetry planes in conjunction with the data generation facilities allow XWAVE to be applied to bodies of revolution with considerable ease and efficiency, although the program is most advantageous when used with more irregular geometries.

The matrix equation approximating the Helmholtz surface integral equation has been modified to include the effect of surface mobility as described in the following section.

TABLE 1 - CDC 6700 COMPUTER RUNNING TIME WITH XWAVE

Symmetry Planes	Basic Elements	Effective Elements	Number of Iterations	Computing Units (A+B) time (Minutes)
0	130	130	30	2.11
0	300	300	30	10.65
0	600	600	30	41.55
3	792	6336	26	55.95
3	39	5616	30	0.22

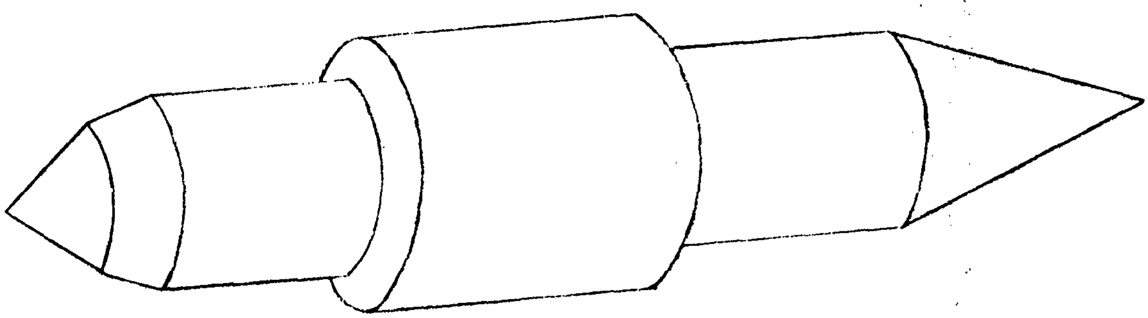

Figure 1 - Typical Structural Surface which can be Generated Automatically by XWAVE

III. STRUCTURE-FLUID INTERACTION FORMULATION

The Helmholtz integral equation for surface pressure is

$$\frac{p(\underline{y}')}{2} - \iint_S p(\underline{y}') \frac{\partial}{\partial n} \left(\frac{e^{ik|\underline{y}'-\underline{y}|}}{4\pi |\underline{y}'-\underline{y}|} \right) dS = - \iint_S q(\underline{y}) \frac{e^{ik|\underline{y}'-\underline{y}|}}{4\pi |\underline{y}'-\underline{y}|} dS \qquad (1)$$

In this equation $\underline{y}'$ and $\underline{y}$ are vector points on the closed surface S; k is the wave number, p is surface pressure, and $q(\underline{y})$ is the normal gradient of surface pressure,

$$q(\underline{y}) = i\omega\rho\, v(\underline{y})$$

where $v(\underline{y})$ is the normal surface velocity on S, ω is the angular frequency, and ρ is the fluid mass density.

When S is not a quadric surface, an approximate solution[2] of Equation (1) can be obtained for a specified normal velocity boundary condition by subdividing S into small areas, A_j, and replacing the integrals by a finite sum of terms evaluated only at points $\underline{y}_j'$ and $\underline{y}_j$ within the respective areas. The resulting matrix equation is

$$-\tfrac{1}{2}\{\bar{p}_j\} + [G2_{ji}][A_{jj}]\{\bar{p}_j\} = ik\,[G_{ji}][A_{jj}]\{\bar{v}_j\} \qquad (2)$$

The overbar $\bar{\ }$ denotes nondimensional surface pressure

$$\bar{p}_i = p_i/\rho c v_0 \qquad (3)$$

and surface normal velocity

$$\bar{v}_i = v_i/v_0 \qquad (4)$$

where c is the speed of sound in water and v_0 is an arbitrary reference velocity. Equation (2) reduces to

$$[M_{ji}]\{\bar{p}_j\} = [B_{ji}]\{\bar{v}_j\} \tag{5}$$

The computer program XWAVE sets up the coefficients of Equation (5), using automatic data generation for bodies of revolution, and solves for the surface pressures $\bar{p}_i$ (for $[M_{ji}]$ non-singular) via Gauss-Seidel iteration or a direct method when necessary. It is anticipated that special techniques will be incorporated into XWAVE for handling cases in which $[M_{ji}]$ is approaching singularity. Equation (5) is currently solved either entirely in core or through use of auxilliary storage (disks) depending upon the order of $[M_{ji}]$ and $[B_{ji}]$ and the amount of core one wishes to use.

To incorporate the dynamic effect of fluid pressure on the shell surface, the following equations are invoked:

$$\{w_j\} = \{u_j\} - [q_{ji}][A_{jj}]\{p_j\} \tag{6}$$

This is the matrix form, for a surface divided into j sub-areas, of a relationship described by Chen[1]. The subscript j references the location of the basepoint (taken here to be the centroid) of sub-area j. With this in mind, w_j is the component of fluid particle velocity normal to the surface at j; u_j is the surface normal component of the in vacuo velocity response to harmonic forcing functions (i.e., applied mechanical forces; $[q_{ji}]$ is the in vacuo surface normal mobility matrix; A_{jj} is a diagonal matrix of surface element areas;

and p_j is the surface acoustic pressure (complex-valued) at the j^{th} element. The matrix elements q_{ji} are defined as the normal surface velocity at base point j per unit harmonic force (at angular frequency ω), acting normal to the surface at base point i. With this definition, the second term on the right hand side (r.h.s.) of Equation (6) gives the surface normal component of velocity due to acoustic pressure. Equation (6), then, states that the resultant normal surface velocity at base point j is the algebraic sum of the normal component in vacuo due to applied mechanical forces and the normal component in vacuo due to acoustic forces, and equates this resultant velocity to the fluid particle velocity at j. Since w_j is equal to the shell-fluid surface normal velocity, it can be substituted for $\bar{v}_j$ in Equation (2) after normalizing by v_0,

$$-\tfrac{1}{2}\{\bar{p}_j\} + [G2_{ji}][A_{jj}]\{\bar{p}_j\} = ik[G_{ji}][A_{jj}]\left\{\{\bar{u}_j\} - [\bar{q}_{ji}][A_{jj}]\{p_j\}\right\}. \quad (7)$$

Since the magnitude of p_j is $\rho c\,\bar{p}_j$, one then obtains

$$-\tfrac{1}{2}\{\bar{p}_j\} + [G2_{ji}][A_{jj}]\{\bar{p}_j\} = ik[G_{ji}][A_{jj}]\left\{\{\bar{u}_j\} - \rho c[\bar{q}_{ji}][A_{jj}]\{\bar{p}_j\}\right\} \quad (8)$$

which is the combined structure-fluid interaction equation. Equation (8) can be rearranged as

$$-\tfrac{1}{2}\{\bar{p}_j\} + [G2_{ji}][A_{jj}]\{\bar{p}_j\} + ik\rho c[G_{ji}][A_{jj}][\bar{q}_{ji}][A_{jj}]\{\bar{p}_j\} = ik[G_{ji}][A_{jj}]\{\bar{u}_j\} \quad (9)$$

Comparing this expression with Equation (2) and its reduced form, Equation (5), it is seen that the reduced form of Equation (9) is

$$[\tilde{M}_{ji}]\{\bar{p}_j\} = [B_{ji}]\{\bar{u}_j\} \quad (10)$$

The tilde over M_{ji} signifies modification by addition of the matrix $ik\rho c[G_{ji}][A_{jj}][\bar{q}_{ji}][A_{jj}]$.

The current version of XWAVE, when running under the option to incorporate surface mobility, expects to find the dynamic mobility matrix $[q_{ji}]$, as well as the in vacuo velocity response vector $\{u_j\}$ due to mechanical forces at frequency ω, stored columnwise on an auxilliary device (disk). As the program generates the usual rows of $[G2_{ji}][A_{jj}]$ and $[G_{ji}][A_{jj}]$ which go into the formation respectively of $[M_{ji}]$ and $[B_{ji}]$, it reads the columns of $[q_{ji}]$, computes corresponding rows of the modifying matrix (third term, l.h.s. of Equation (9)), and adds them in to produce rows of $[\tilde{M}_{ji}]$. Using the known vector, $\{\bar{u}_j\}$, Equation (10) is then solved by iteration for the interaction pressures $\bar{p}_j$.

Obviously, including mobility in applications where few or no symmetry planes exist considerably complicates the already formidable task of solving Equation (5) which in such cases yields a very large matrix system with complex-valued coefficients. Apart from the need to efficiently generate and handle the large number of elements of $[q_{ji}]$, the modified matrix $[\tilde{M}_{ji}]$ will have its own set of critical wave numbers. These wave numbers will be different from those of $[M_{ji}]$ which are unique to the surface shape. While the density patterns for occurrence of the latter wave numbers have been established at least for certain shapes such as spheres, cubes, and cylinders, the density patterns for the critical wave numbers of $[\tilde{M}_{ji}]$ pose a problem for further investigation. This problem is, of course, not confined to asymmetric boundary conditions.

Another anticipated problem is that of generating the elements of $[q_{ji}]$ at frequencies close to natural frequencies of the structure. A good estimate for structural damping would certainly be required to obtain numerical significance for dynamic mobility in such cases.

IV. DEMONSTRATION CALCULATION

A. INTRODUCTION

Our work to date in the area of structure-fluid interaction, aside from the required developmental work on XWAVE has focused on ways of using NASTRAN to generate the normal surface mobility matrix ($[q_{ji}]$), which is the basis for our interaction equations.

Two methods for obtaining the elements of $[q_{ji}]$ have thus far been considered, each involving a particular NASTRAN rigid format for forced frequency response. One of these, using rigid format no. 8, is referred to as the direct method; the other, using rigid format 11, is called the modal method. In both cases, the matrix elements are generated by calculating the velocity response at all surface grid points as a unit harmonic force at the single frequency of interest is successively applied at each finite element grid point. When no symmetries are present in the surface velocity distribution, n NASTRAN solutions are required, n denoting the total number of grid points on the structural surface. Each solution produces one column of $[q_{ji}]$. If symmetries are present, then only m ($m<n$) NASTRAN solutions are required, m denoting the degree of nonredundancy in the surface velocity distribution. The minimum value for m, $m=1$,

is obtained for the surface of a sphere. Here only <u>one</u> NASTRAN run is required since, from a single column of $[q_{ji}]$, all others can be obtained by an interpolation process.

Since the generation of the mobility matrix and the matrix multiplications associated with the calculation of $[\tilde{M}_{ji}]$ represent a considerable portion of the total cost involved in a fluid-structure interaction calculation, the spherical shell is an ideal structure for studying interfaces with NASTRAN.

The next section describes the XWAVE-NASTRAN interface for a spherical shell submerged in an infinite fluid medium and excited by a simple time-harmonic radial point load. The interface consists of

1) NASTRAN which is used to calculate both the <u>in vacuo</u> velocity response to the exciting force, and the in vacuo velocity response to a unit exciting force (one column of $[q_{ji}]$);
2) the subroutine, MOBIL, which utilizes the latter response vector as a basis for computing the remaining columns of $[q_{ji}]$; and
3) XWAVE, which sets up the interaction equations and solves for interaction pressures at the surface of the sphere.

All phases and details of this interface will be described as part of the general survey of a demonstration calculation. That is, the sphere problem will serve to demonstrate and describe an interface which is of considerably more general application.

Although NASTRAN has been used here for obtaining the mobility matrix, it is important to emphasize that, from the standpoint of the acoustic radiation program, XWAVE, the calculation of mobility

remains a separate and independent process. As noted in Section III, when the fluid loading option of XWAVE is selected, the program expects to find the columns of $[q_{ji}]$ stored on an auxilliary device (tape or disk), although it does not matter how they were produced. They could be obtained from any structural dynamic analysis process (finite-element or otherwise) or could even be determined experimentally. The interface proposed here retains the advantages (noted by Chen[3]) of keeping separate the calculation of the structural and acoustic components which go into the interaction equations.

B. CALCULATION OF SURFACE PRESSURES ON A SUBMERGED VIBRATING SPHERE

Figure 2 shows the physical problem selected for calculation. Figure 3 gives the reference coordinate system used for the sphere and also the finite-element model of the surface used for calculation. Since the normal surface velocity distribution for the excitation selected is known to be dependent only upon colatitude, θ, only one strip of finite elements is needed as shown. The types of elements employed were NASTRAN's triangular and quadrilateral plate elements having membrane and bending stiffness. The bounding meridians of the lune enclosing the element strip are in symmetry planes about which out-of-plane translation and in-plane rotation about r and θ are constrained.

NASTRAN is now used with this data to calculate the radial (normal) velocity response (in vacuo) of the sphere to a radial driving force F at angular frequency ω. In general, F will have arbitrary magnitude, but for this calculation it is taken to be unity so that the

[3] Chen, L., "A Matrix Method of Analysis of Structure-Fluid Interaction Problems," ASME paper number 61-WA-220 (August 29, 1961).

Sphere

Radius	1"
Material	steel
Force	1 lb
ω	angular frequency
Shell thickness	0.1"

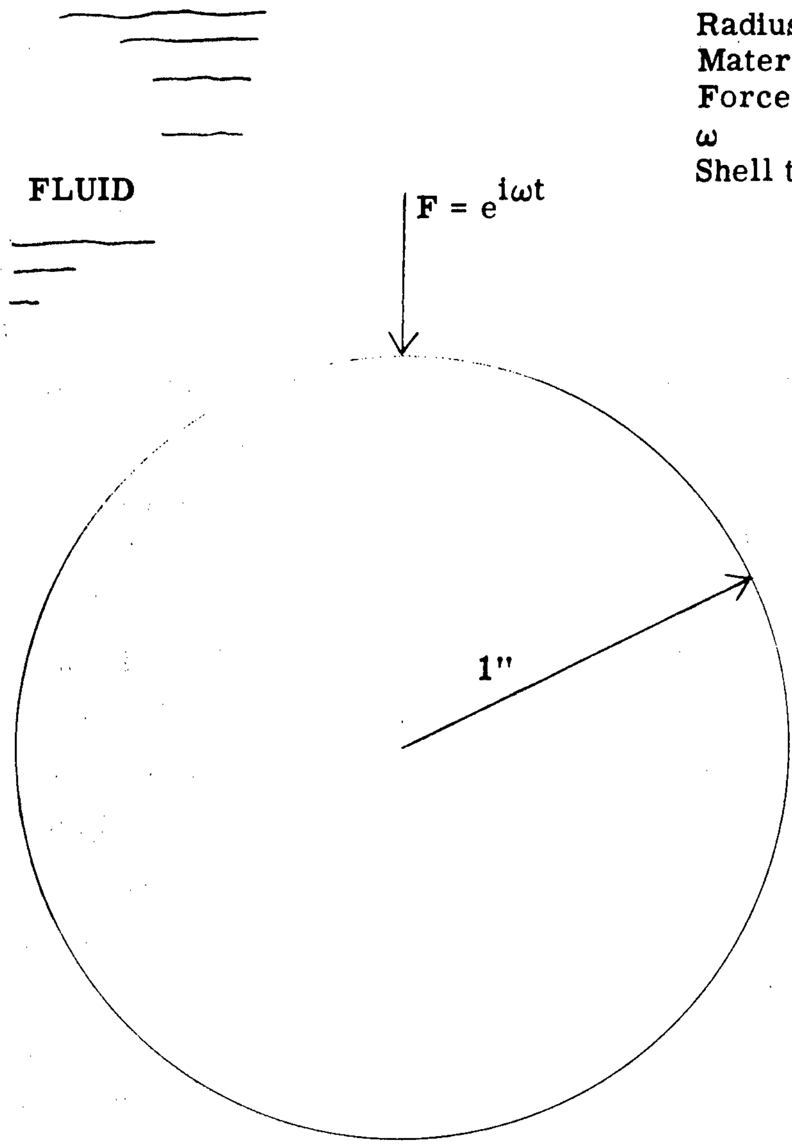

Figure 2 - Submerged Vibrating Spherical Shell

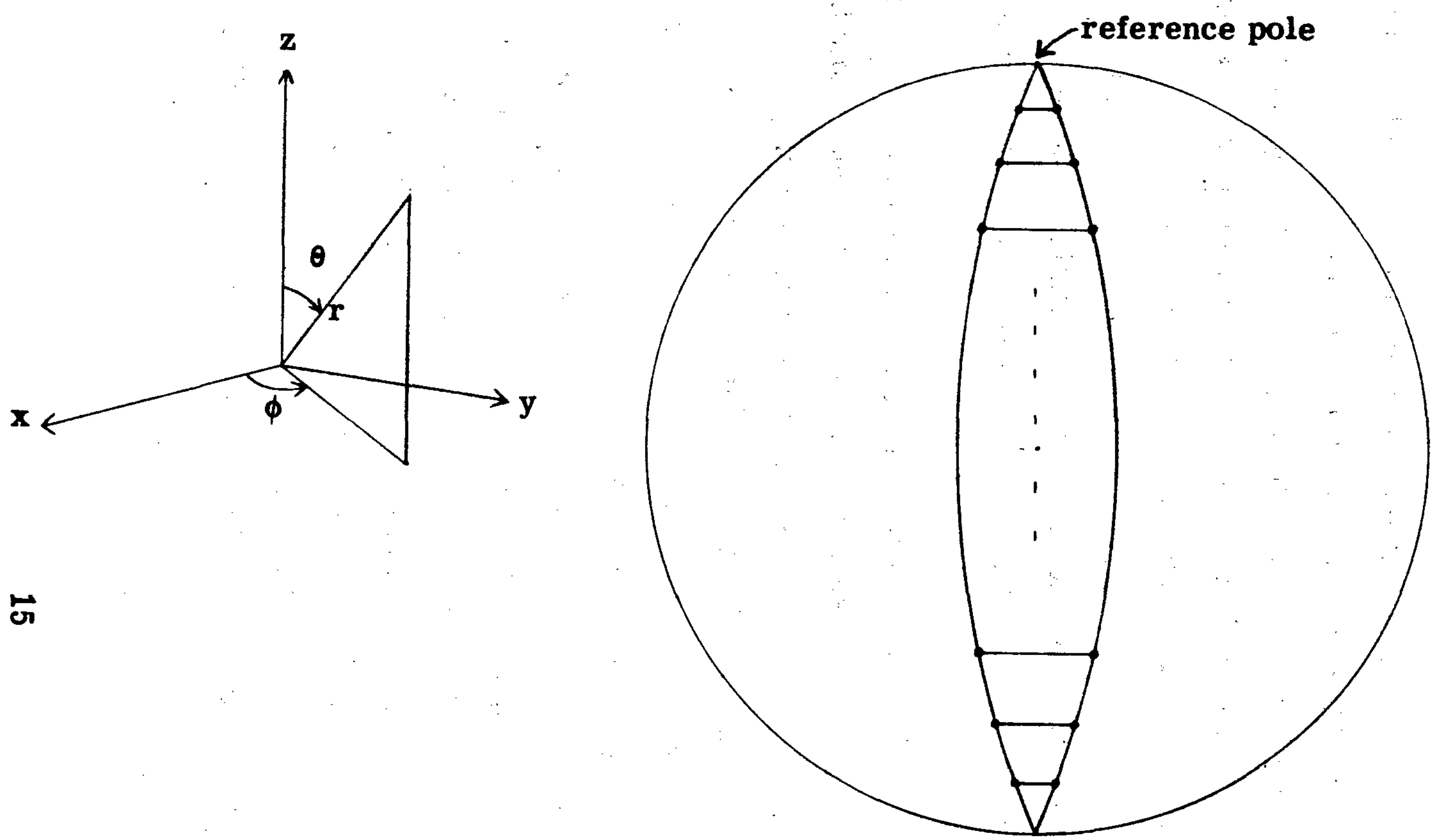

Figure 3 - Sphere Coordinate System and Finite-Element Model

NASTRAN results can also be used for the required in vacuo vector, $\{u_j\}$, and for computing all columns of the mobility matrix. NASTRAN computes the velocity response (magnitude and phase) at each grid point of the finite element model and provides this information on punched cards as part of its edited output. From these cards, only those containing the velocities for grid points along one meridian are kept, since the corresponding velocities at the neighboring grid points at the same latitude are equal and therefore redundant.

The grid of surface acoustic elements required for the pressure calculation by XWAVE will be, in general, much finer than that needed for the structural dynamic calculations. Also, there must be a one-to-one correspondence between elements of the surface acoustic model and those of the mobility matrix. An interpolation process facilitates the linking together of the two models with their respective element densities.

For the sphere with radial exciting force, this linkage of structural and acoustic models is accomplished as follows. As previously noted, the velocity response at any point j resulting from the exciting force (Figure 2) is a function only of the colatitude, θ, of j from the point at which the exciting force acts. Now consider any two points i and j located in respective acoustic surface elements on the sphere as shown in Figure 4. To obtain mobility matrix element q_{ji}, one need calculate only the angle θ_{ji} with point i taken as the reference pole at which the force acts. Then knowing θ_{ji}, q_{ji} (velocity at j due to force at i) is either given explicitly in the vector, $\{u\}$, from NASTRAN or can be obtained from $\{u\}$ by interpolation. In this way, all elements of the dynamic mobility matrix of order $n \times n$ can be obtained from the basic vector $\{u\}$ of order $m \times 1$ where $n \geq m$. This

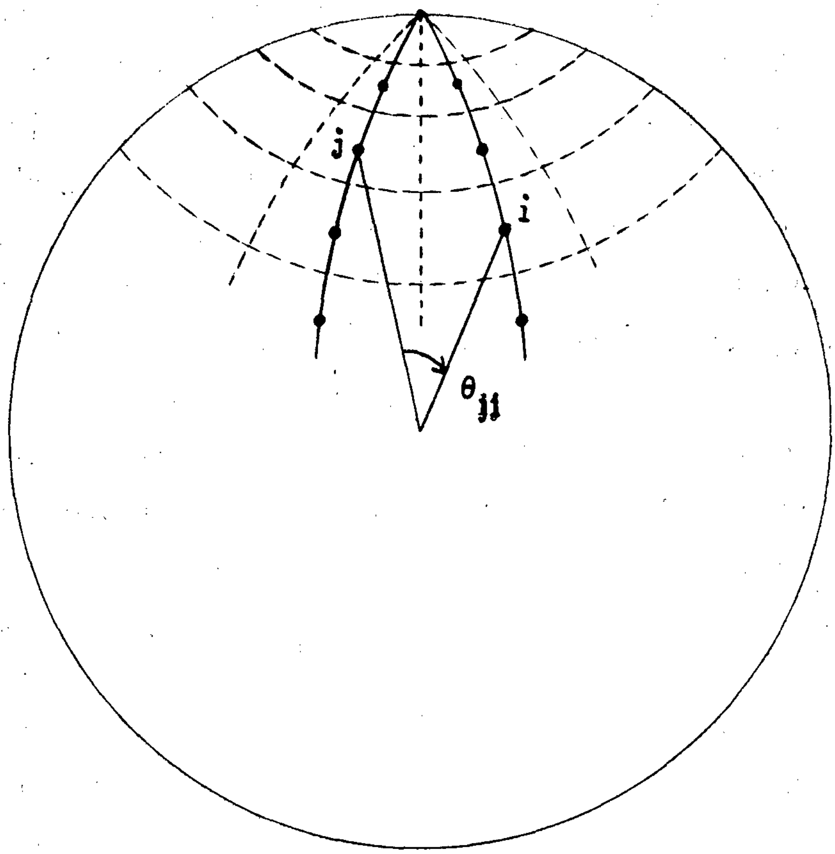

Figure 4 - Acoustic Element Modeling of Spherical Surface

important feature permits varying the acoustic element density as well as {u} (within limits) without rerunning NASTRAN.

Included with the velocity response vector punched on cards by NASTRAN is the set of NASTRAN GRID cards containing the corresponding colatitudes of the related structural gridpoints. These data are fed into a special subroutine MOBIL along with increments in longitude and latitude necessary to establish the acoustic surface element grid illustrated in Figure 4. XWAVE will utilize this same grid later. MOBIL first generates the surface coordinates of station points (centroids) for the surface acoustic elements, indicated by dots (Figure 4). Then the angles θ_{ji} are computed for selected pairs of station points and the corresponding values q_{ji} are obtained by interpolation (4-point) of the stored vector {u}.

The term "selected" pairs of station points is used here because the velocity (and hence pressure) distribution resulting from the exciting force under consideration permits the order of the mobility matrix to be reduced to just the number of station points along a single meridian. Since this may not be immediately obvious, the following explanation is offered:

The surface pressure distribution reflects the same symmetries and anti-symmetries as the velocity distribution vector {u}. For the application under consideration, the actual number of degrees of freedom or number of distinct values in the velocity and pressure vectors is thus the number of stations along a meridian. Equation (7) shows that the matrices $[G2_{ji}][A_{jj}]$ on the left hand side and $[G_{ji}][A_{jj}]$ on the right hand side must also be reducible to this number of degrees of freedom. The term $[G_{ji}][A_{jj}][\bar{q}_{ji}][A_{jj}]$ must also be

reducible, but if this term can be computed as $[G_{ji}]^R[A_{jj}]^R[\bar{q}_{ji}]^R[A_{jj}]^R$, R denoting reduced order, computer storage and data handling problems associated with large $[q_{ji}]$ and matrix multiplication times can be considerably lessened. Although, in general, $\{[G_{ji}][A_{jj}][\bar{q}_{ji}][A_{jj}]\}^R \neq [G_{ji}]^R[A_{jj}]^R[\bar{q}_{ji}]^R[A_{jj}]^R$ the mobility matrix for a sphere has such properties that $[\bar{q}_{ji}][A_{jj}]\{\bar{p}_j\}$ has the same number of degrees of freedom as $\{\bar{p}_j\}$ and this property apparently carries over for any surface of revolution.

Utilizing this useful property of the mobility matrix, subroutine MOBIL computes the reduced form at a considerable saving of time and produces punched cards by columns for use as data input to XWAVE.

For the surface pressure calculation by XWAVE, the shell surface was modeled by 1188 effective acoustic elements. This number is reducible by the velocity symmetry to a basic set of elements along a single meridian. The number of such elements was taken as 33, giving a one-to-one correspondence between them and the NASTRAN grid points along the same meridian. Without interpolation, the NASTRAN velocity at each grid point was taken as representing the constant velocity over the corresponding acoustic elements. The nonuniform spacing of the gridpoints, however, meant that the representative velocity over each acoustic element was being taken from a point offset from the element centroid. Around each band of latitude, 36 effective elements were taken to complete the acoustic model. The acoustic equations, with mobility added in, then reduce to a 33 x 33 system which is very economical for test purposes.

The steps in the interface process may be summarized as follows:

- Set up a structural model as in Figure 3
- Assign a frequency for the radial driving force in CPS, obtain from a NASTRAN run (step 1) the normal velocity response $\{u\}$. If the driving force magnitude is unity, $\{u\}$ will also be a column of the mobility matrix, $[q_{ji}]$.
- Supply $\{u\}$ along with the NASTRAN GRID cards and the acoustic surface grid increments to MOBIL and obtain (step 2) the reduced mobility matrix, $[q_{ji}]^R$.
- Supply $\{u\}$ and $[q_{ji}]^R$ along with the wave number k to XWAVE which calculates (step 3) the surface interaction pressures.

NASTRAN and MOBIL were run on the CDC 6400 system; XWAVE was run on the CDC 6700 system. The NASTRAN complex frequency response (step 1) required 137.417 computing unit seconds; the computation of the mobility matrix, step 2, required 536.049 computing unit seconds; and the computation of surface pressures by XWAVE, step 3, required 96.339 computing unit A seconds plus 27 computing unit B seconds.

C. RESULTS

Surface pressures were determined for $ka = 2$ and $ka = 0.4$, using water as the fluid medium, and compared with results obtained from an expression by M. Junger[4] for the same problem. The

[4] Junger, Miguel, C., "Vibrations of Elastic Shells in a Fluid Medium and The Associated Radiation of Sound," Journal of Applied Mechanics, Vol. 19, No. 1 (March 1952).

analytical values were computed using Junger's formula,

$$p = \frac{\rho c F e^{j\omega t}}{4\pi a^2} \sum_{n=0}^{\infty} \frac{(2n+1)\,\zeta_n(kr)}{Z_{n\ell}} P_n(\cos\theta) \tag{11}$$

where ρ is the fluid density,

c is the velocity of sound in the fluid,

F is the driving force magnitude,

ω is the angular frequency of vibration,

j is $-\sqrt{-1}$,

a is the sphere radius,

ζ_n are acoustic impedance ratios,

$Z_{n\ell}$ are the loaded mechanical impedances of the shell,

P_n are Legendre polynomials with argument $\cos\theta$, and

θ is the colatitude at which pressure, p, is computed.

In evaluating Equation (11), the quantities ζ_n were calculated according to the theory described by Junger[5]. Comparisons of the XWAVE and analytical solutions are given in Figures 5 and 6.

The comparison of numerical and analytical results reveals that the acoustic surface model selected for this demonstration is useful only for low values of ka. Even in the low range, there is need for refinement of the model near the force application point.

[5] Junger, Miguel, C., "Radiation Loading of Cylindrical and Spherical Surfaces," The Journal of The Acoustical Society of America, Vol. 24, Number 3, (May 1952).

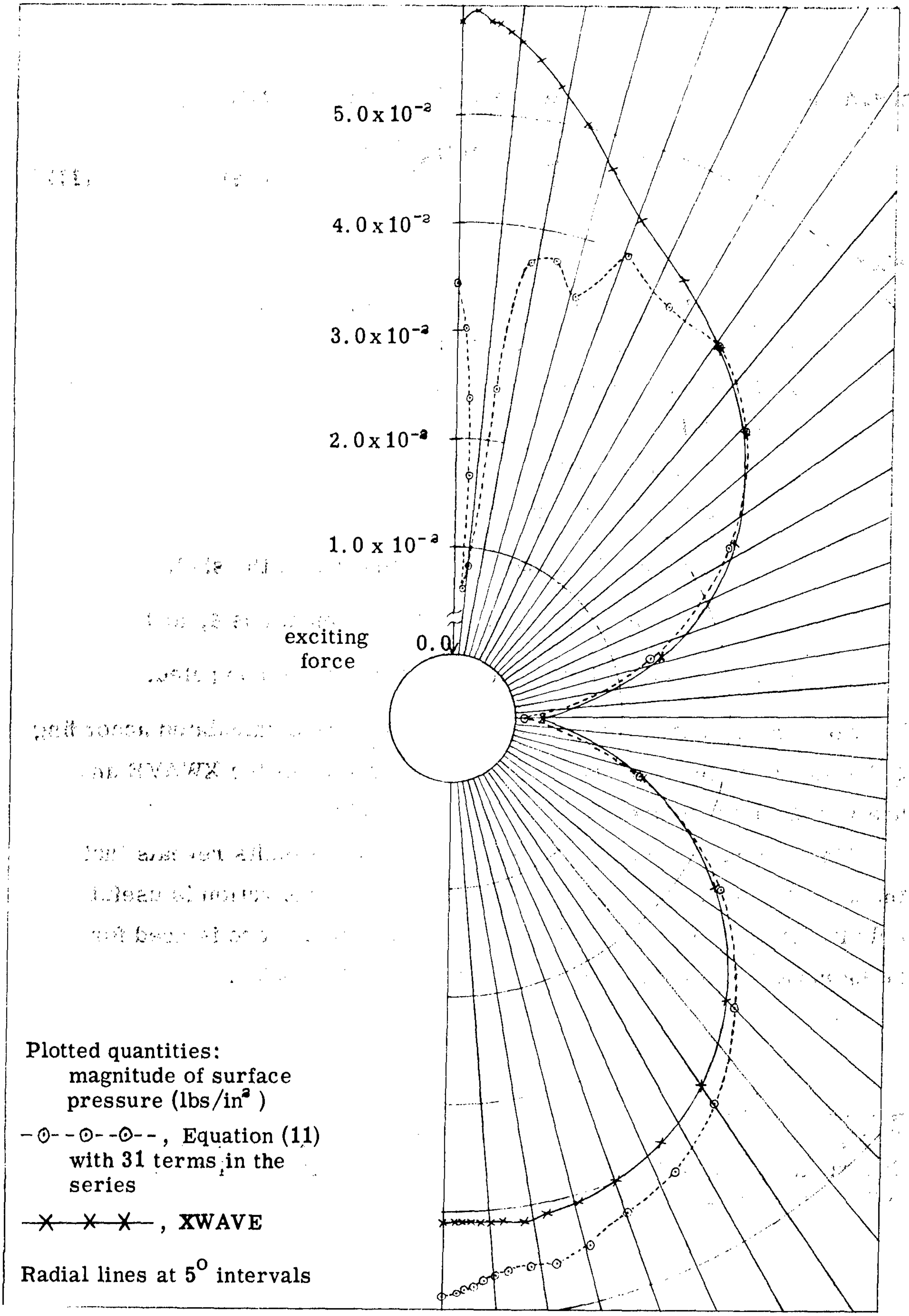

Figure 5 - Comparison of XWAVE and Analytical Results, ka = 0.4

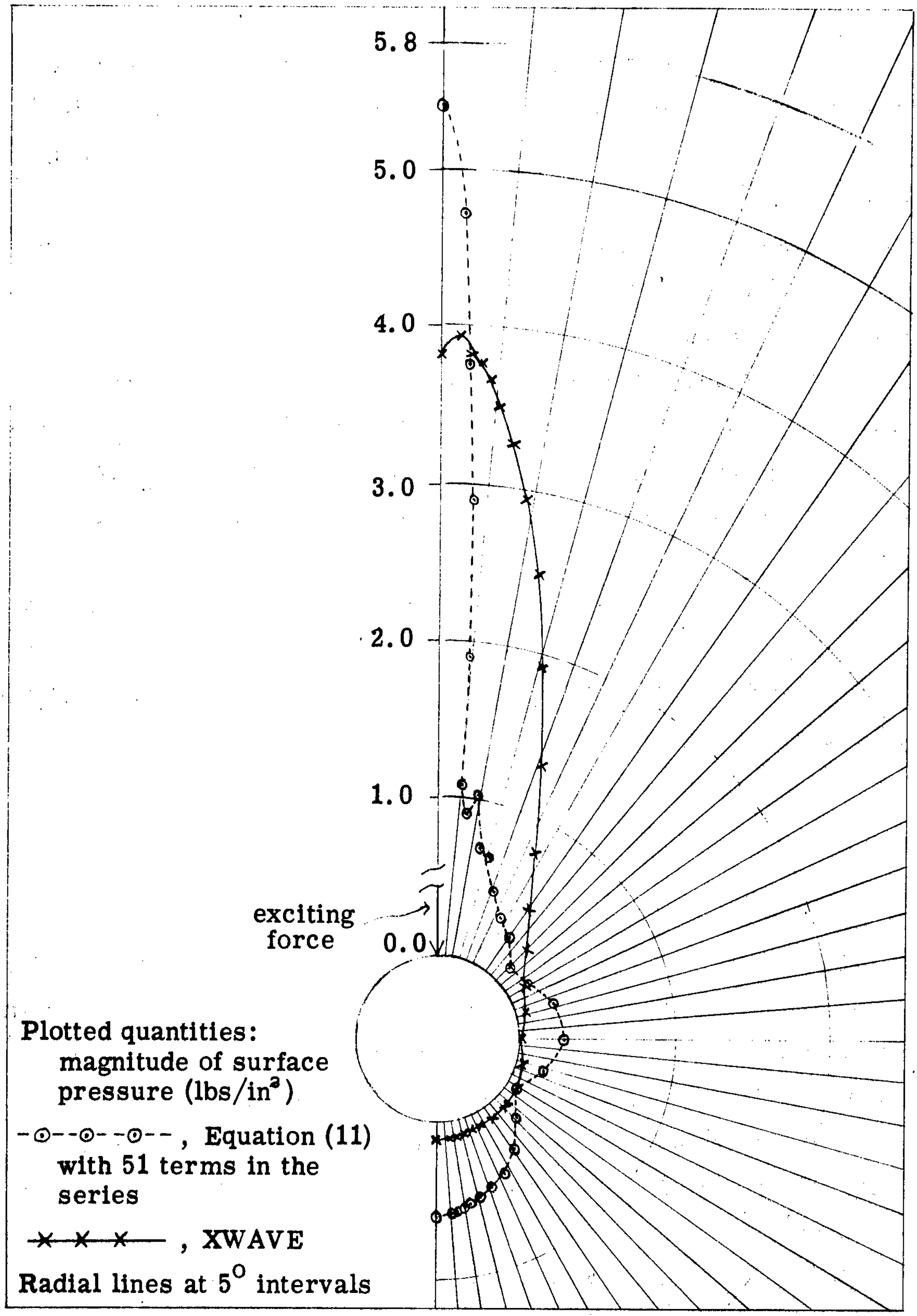

Figure 6 - Comparison of XWAVE and Analytical Results, ka = 2

For ka = 2, the addition of mobility to the acoustic equations caused the loss of conditioning of the matrix $[\tilde{M}_{ji}]$ (Equation (10)) required for convergence of the iterative solution algorithm. This explanation was confirmed when a converged solution for ka = 2 was achieved by iteration with mobility removed. The XWAVE curve in Figure 6 was obtained by incorporating into the program a subroutine for direct solution of Equation (10).

This interface between the acoustic program XWAVE and NASTRAN, applied to the submerged vibrating sphere, demonstrates that the approach suggested can give reasonable results subject to a proper selection and coordination of the structural and acoustic models.

The next logical step in this work, paralleling model refinement, is to test the interface using arbitrary surfaces of revolution, and then to study surfaces of arbitrary geometry (structures of more practical application).

ACKNOWLEDGMENTS

The author wishes to express appreciation to Dr. Gordon C. Everstine of The Theory of Structures Branch for significant contributions to the effort reported, including consultation on the use of NASTRAN and provision of two of his subroutines. One of these performs the interpolation required to obtain the mobility matrix and the other was used to obtain the direct solution of the interaction equations for the case ka = 2.

A special word of appreciation is also to be accorded to Dr. John W. Wrench, Jr., Head of the Mathematical Computation

Division, who calculated to a high degree of accuracy the spherical Bessel functions for argument 2 and order ranging from 30 to 50 that were required for computation of the analytic curve for surface pressure for the case $ka = 2$.

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13. ABSTRACT

This report describes a method for incorporating the structure-fluid interaction effect into NASTRAN dynamic frequency response calculations for submerged structures. The interaction equation is derived by incorporating the effect of dynamic surface mobility into the equations which approximate the surface Helmholtz integral equation and by requiring velocity compatibility at the fluid-surface interface. The method is implemented through an interface between the computer program, XWAVE, for acoustic pressure calculations and NASTRAN. The method is demonstrated by calculating the shell-surface-fluid interaction pressures on a hollow sphere submerged in an infinite fluid and excited by a radial point harmonic forcing function. The surface pressure results are compared with values calculated using an analytic formula of M. C. Junger.

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